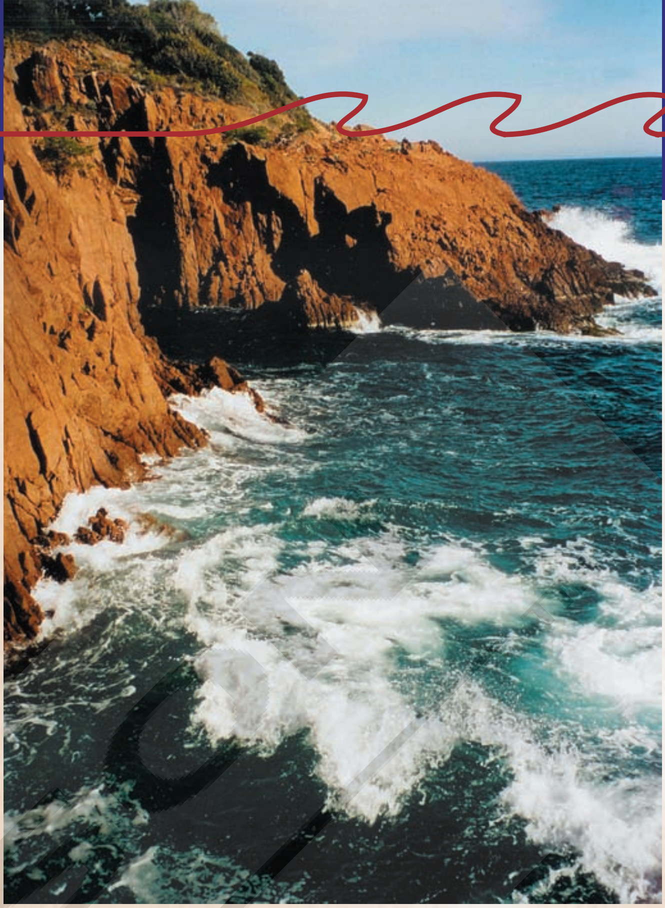
WAVES, BEACHES, AND COASTAL EROSION

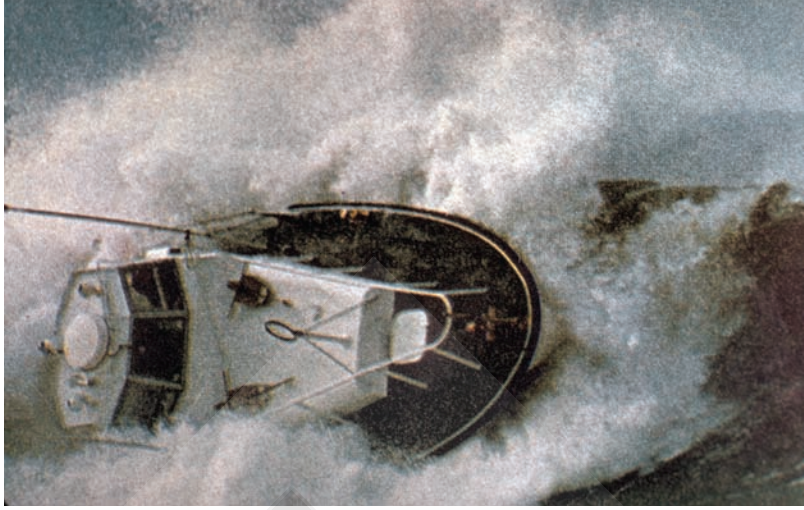
Rivers of Sand



The material that is contained on the following pages was reprinted from the text entitled *Natural Hazards and Disasters* by Donald Hyndman and David Hyndman. In their book the focus is on Earth and atmospheric hazards that appear rapidly, often without significant warning. With each topic they emphasize the interrelationships between hazards, such as the fact that building dams on rivers often leads to greater coastal erosion and wildfires generally make slopes more susceptible to floods, landslides, and mudflows. By learning about the dynamic Earth processes that affect our lives, the reader should be able to make educated choices about where to live, build houses, business offices, or engineering projects. People do not often make poor choices willfully but through their lack of awareness of natural processes.

Living on Dangerous Coasts

Hurricanes and other major storms affect beaches and the people who live on them. To understand coastal hazards, we need to understand wave processes and the formation of beaches and sea cliffs. We also need to understand how human activities affect wave action, beach response, and sea-cliff collapse. As populations grow in numbers and affluence, more people move to the coasts, not only to live but also for recreation. But beaches and sea cliffs constantly change with the seasons and progressively with time. When people build permanent structures at the beach, coastal processes do not stop; the processes interact with and are affected by those new structures. Storms, hurricanes, and their dramatic aftermath are often viewed as abnormal or "nature on a rampage." In fact, they are normal for a constantly evolving landscape. What is abnormal is how human actions and structures cause natural processes to impose unwanted damages.



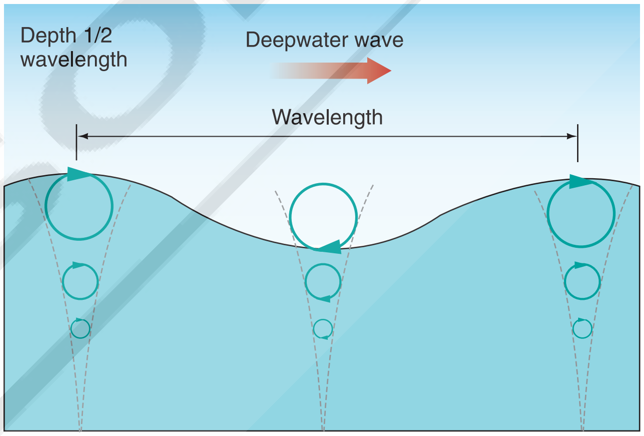
NOAA.

▶**FIGURE 13-1.** In addition to shore damage, huge storm waves can topple boats.

Waves

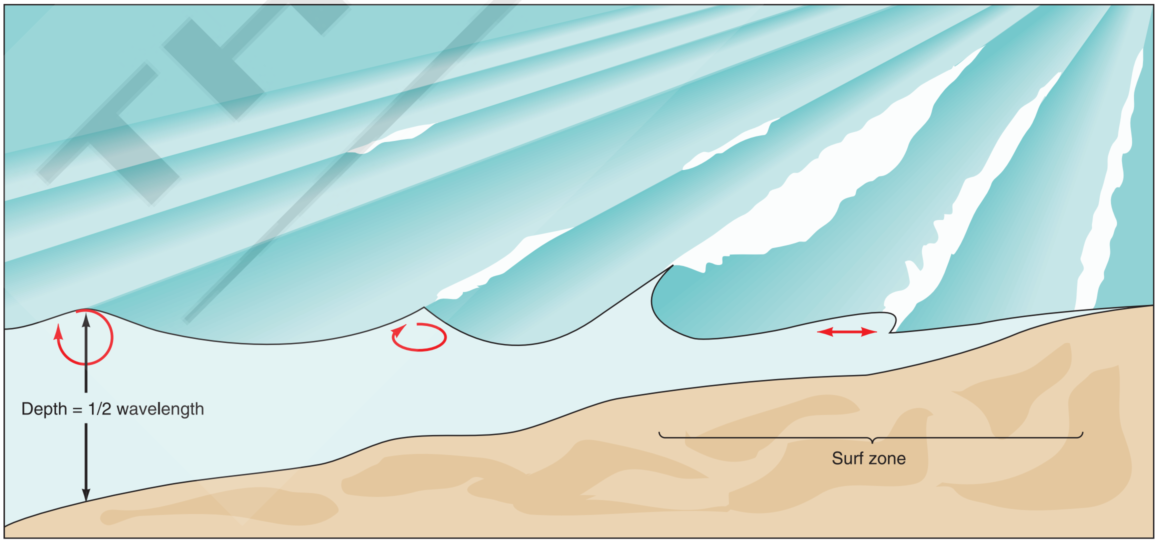
Winds blowing across the sea push the water surface into waves because of friction between the air and the water. Gentle winds form small ripples. As the wind speed increases, ripples grow into waves. Two other factors that increase wave height are **fetch,** which is the length of water surface over which the wind blows, and the *amount of time* the wind blows across the water surface. Ocean waves are generally much larger than those on small lakes, and prolonged storms often build large damaging waves (▶ Figure 13-1).

The timing and size of waves approaching a shoreline varies by the location and size of offshore storms. Waves move out from major storm centers, becoming broad, rolling swells with large **wavelengths** (▶Figure 13-2). A con-



NOAA.

▶**FIGURE 13-2.** Individual water particles rotate in a circular motion but do not travel in the direction of wave travel. The water motion fades out downward until a depth of approximately half a wavelength.



Thomas Garrison.

▶**FIGURE 13-3.** Characteristics of waves change on approaching a shore.

Reprinted from *Natural Hazards and Disasters,* Hyndman & Hyndman, ISBN 0-534-99760-0

stant mild onshore wind will produce smaller and shorter-wavelength waves.

As waves approach the beach, water in a wave itself does not move onshore with the wave; it merely moves in a circular motion within the wave, otherwise staying in place (▶ Figure 13-3). You can see that motion by watching a stick or seagull floating on the water surface. It moves up and down, back and forth, not approaching the shore unless blown by the wind or caught in shallow water where the waves break. Waves in this circular motion are not damaging because the mass of water is not moving forward. Watch waves moving past the pilings of a pier or against any kind of vertical wall in deep water. The waves have little forward momentum and do not splash against the vertical surface; they merely ride up and down against it. A steep "wall" of coral reef facing offshore from some tropical islands has a similar effect, thereby helping protect such islands from the impact of storm waves. When waves approach shore they begin to "feel bottom," and thus gain forward motion, which causes the waves to break. These are conditions under which waves gain the potential for serious damage.


Donald Hyndman photo.

▶**FIGURE 13-4.** As waves approach the shore, they drag on bottom and their crests lean forward to break as seen here along the southern Oregon coast. The water is brown from stirred sand.


U.S. Army Corps of Engineers photo.

▶**FIGURE 13-5.** Storm waves pound the seawall at Galveston, Texas. The seawall is in the lower left, under the breaking wave.

Sidebar 13-1

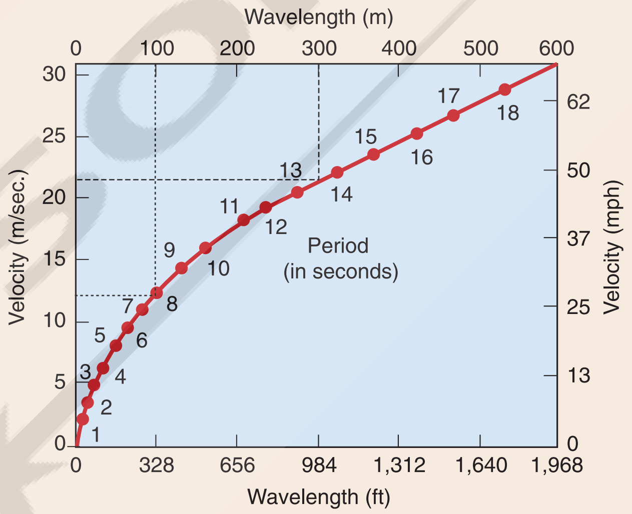
Wave velocity in deep water is proportional to the square root of wavelength:

$$\mathbf{V} = \sqrt{\frac{\mathbf{gL}}{\mathbf{2\pi}}} = 1.25\sqrt{L}$$

where

V = velocity (in m/sec.)
L = wavelength (in m)
g = acceleration of gravity (9.8 m/sec^2)
π = 3.1416

Thus, a group of waves with a wavelength of 5 meters moves at 1.25 × 2.24 = 2.8 m/sec. or 10.1 km/hr. Waves with a wavelength of 100 meters move at 1.25 × 10 = 12.5 m/sec. or 45 km/hr. We can also show this relationship graphically, as shown below. Note that if we measure the period (the time between wave crests), we can easily determine both the wavelength and wave velocity using the graph below.



Sidebar 13-2

In shallow water, wave velocity is proportional to square root of water depth:

$$\mathbf{V} = \sqrt{\mathbf{gD}} = 3.1\sqrt{D}$$

where

V = velocity
D = water depth (m)

Sidebar 13-3

Doubling the wave height quadruples the energy:

$$(\mathbf{E_w}) = \mathbf{0.125\sigma gH^2L}$$

where

E_w = energy of the wave
σ = water density (close to 1)
g = acceleration of gravity = 9.8 m/sec.^{2}
H = wave height
L = wavelength (in m)

Waves begin to feel the bottom when the water depth is less than approximately half the wavelength. Because the size of the circular motion is controlled by wave size, the depth at which wave action fades out is controlled by wavelength. In shallower water, the crest of the wave moves forward as the base drags on the bottom. The waves slow in shallow water but rise in height (Sidebars 13-1 and 13-2). The momentum of the upper mass of water carries it forward to erode the coast (▶Figures 13-3 and 13-4).

Big waves are more energetic and cause more erosion (▶Figures 13-4 and 13-5). **Wave energy** is proportional to the mass of moving water. This can be approximated by multiplying the density of water by the volume of water in a wave, which is approximately the wave height (H) squared times wavelength (L). Because the height term is squared, waves that are twice as high have four times the energy; those that are four times as high have sixteen times the energy (Sidebar 13-3).

Beaches

Beaches are accumulations of sand or gravel supplied by sea cliff erosion and by river transport of sediments to the coast. The size and number of particles provided by sea-cliff erosion depends on the energy of wave attack, the resistance to erosion of the material making up the cliff, and the particle size into which it breaks. Waves often undercut a cliff that collapses into the surf, then break it into smaller particles (▶Figure 13-6). The size and amount of material supplied by rivers depends similarly on the rate of river flow and the particle size supplied to its channel.

Most of the sand and gravel supplied to the coast is pushed up onto the beach in breaking waves; it then slides back into the surf in the backwash. Big waves during winter storms carry sand offshore into deeper water, leaving only the larger gravels and boulders that they cannot move. The gentle breezes and smaller waves of summer slowly move the sand back onto the beach (▶Figures 13-7 and 13-8).


Donald Hyndman photo.

▶**FIGURE 13-6.** This cliff at Pismo Beach, California, has been undercut by waves. Large chunks of rock break off and are pounded into sand by the waves.


Donald Hyndman photo.

▶**FIGURE 13-7.** A sandy summer beach covers the lower part of a bouldery upper beach left by winter waves north of Newport, Oregon.


USGS photos.

(a) **(b)**

▶**FIGURE 13-8.** This beach north of Point Reyes, California, was eroded by waves during the 1997 El Niño event; in **(a)** much of the sand has been removed (October 1997), but in **(b)** it has been naturally rebuilt by April 1998.

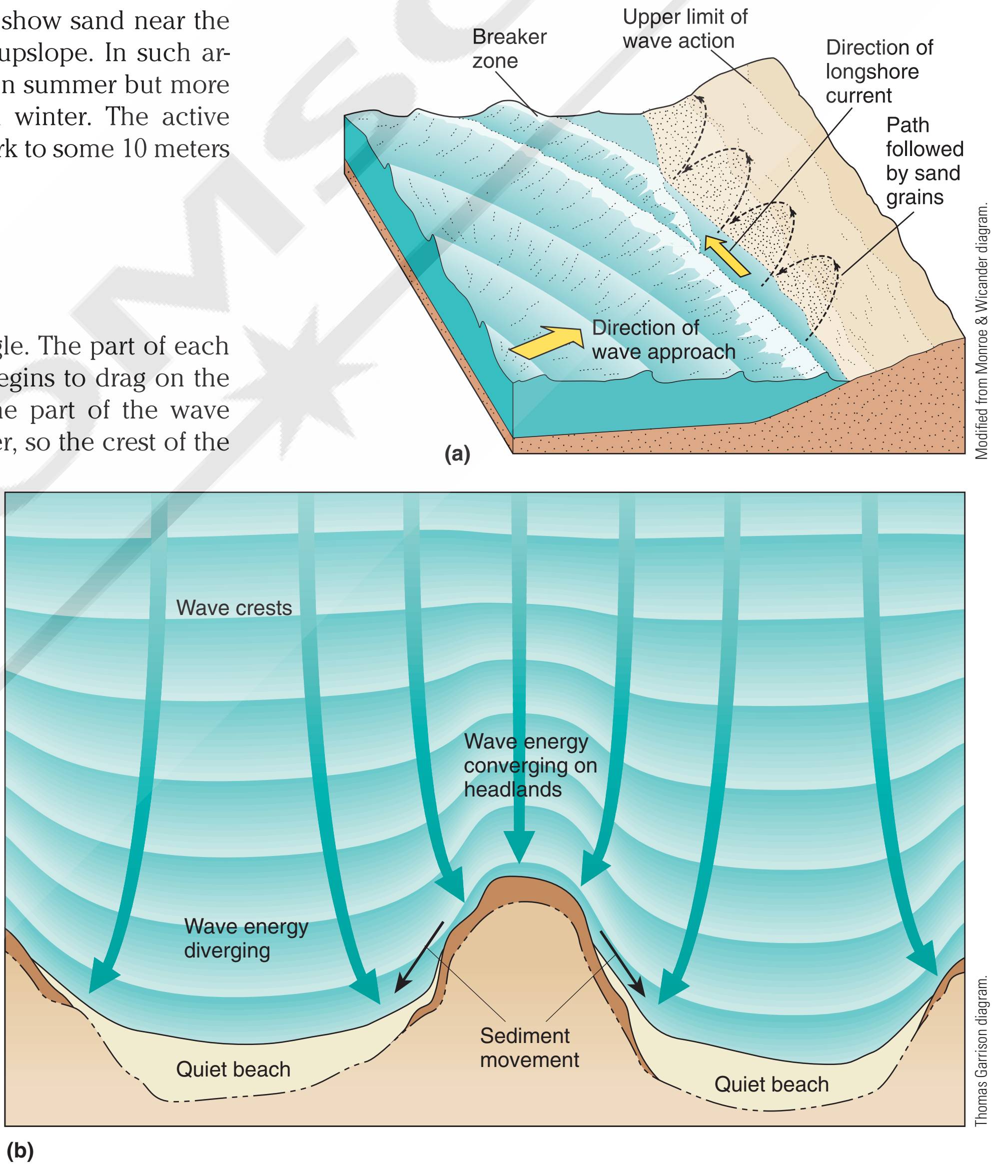

Peter Scholle photo.

FIGURE 13-9. Waves curve by refraction in the shallow water near shore in a New Zealand bay.

As a result, some cliff-bound beaches show sand near the water's edge with gravel or boulders upslope. In such areas, the beaches are commonly sand in summer but more steeply sloping gravel or boulders in winter. The active beach extends from the high-water mark to some 10 meters below sea level.

Wave Refraction and Longshore Drift

Waves often approach shore at an angle. The part of each wave in shallower water near shore begins to drag on the bottom first and thus slows down; the part of the wave that is still in deeper water moves faster, so the crest of the



Modified from Monroe & Wicander diagram.

Thomas Garrison diagram.

FIGURE 13-10. **(a)** Sand grains are pushed up onto the beach in the direction of wave travel. Gravity pulls them back directly down the slope of the beach. The combination is a loop that moves each sand grain along the shore with each incoming wave. **(b)** Wave crests bend to conform to the shape of the shoreline; wave directions bend to attack the shoreline more directly. Thus, rocky headlands are vigorously eroded and bays collect the products of that erosion.

wave curves around toward the shore (▶Figure 13-9). This is called **wave refraction** because waves bend or refract toward shore.

When wave crests approach a beach at an angle, the breaking wave pushes the sand grains up the beach slope at an angle to the shore. As the wave then drains back into the sea, the water moves directly down the beach slope perpendicular to the water's edge.

Thus, grains of sand follow a looping path up the beach and back toward the sea. With each looping motion, each sand grain moves a little farther along the shore (▶Figure 13-10a). The angled waves thus create a **longshore drift** that essentially pushes a river of sand along the shore near the beach. Over the period of a year or so, with high and low tides, large and small waves, and storms, most of the sand on the beach moves farther along shore. Longshore drift also moves sand from headlands to bays (▶Figure 13-10b).

Along both the west and east coasts of the United States, longshore drift is dominantly toward the south. Longshore drift in parts of coastal California averages a phenomenal 750,000 cubic meters of sand past a given point per year, more than 20,000 cubic meters per day. If a large dump truck carries 10 cubic meters, that would be equivalent to 2,000 dump truck loads per day. Along the East Coast, it is much less but still averages 75,000 cubic meters per year, more than 2,000 cubic meters per day.

Waves on Rocky Coasts

Waves approaching a steep coast such as those along much of the Pacific coast of North America or the coast of New England or eastern Canada encounter rocky points called **headlands** that reach into deeper water with shallower sandy bays in between. Waves bend or refract toward the rocky points, causing the energy of the waves to break against the headlands (▶Figure 13-10b). Thus, wave refraction dissipates much of the wave energy that would otherwise have impacted sandy bays. Sand blasted off the rocky point migrates along the shore to be dumped along the beach in the bay because the currents on both sides carry sand to the center of the bay (▶Figures 13-10b and 13-11).

Beach Slope: An Equilibrium Profile

As waves move into shallow water and begin to touch bottom, they move sediment on the bottom, stirring it into motion and moving it toward the shore. Most sediment moves at water depths of less than 10 meters. Long wavelength storm waves, however, with periods of up to twenty seconds, reach deeper; they touch bottom and move sediments at depths as great as 300 meters on the continental shelf.

Whether the sediment moves shoreward or not depends on the balance between shoreward bottom drag by the waves, size of bottom grains, and downslope pull by gravity. Thus, the slope of the bottom is controlled by the energy required to move the grains, which is related to the water depth, wave height, and grain size. Shallower water, smaller waves, and coarser grains promote steeper slopes offshore, just as in rivers. In the breaker zone offshore, waves can easily move the sand and the beach surface is gently sloping. As breakers sweep up onto the shore, the water is shallower, their available energy decreases, and the **shore profile** steepens. Sand there can move back and forth only on such a steeper slope (▶Figure 13-12).

Grain size strongly controls the slope of the beach. Just as in a stream, fine sand can be moved on a gentle slope, coarse sand or pebbles only on a much steeper slope (▶Figures 13-7 and 13-13).

On shallow gently sloping coastlines, such as those in much of the southeastern United States, the beach both onshore and offshore becomes steeper landward (the onshore


David Hyndman photo.

▶FIGURE 13-11. Wave refraction has eroded the former series of headlands along Drakes Bay, Point Reyes National Seashore, California, into a straighter coastline.

Donald Hyndman photo.

FIGURE 13-12. The beach slope steepens shoreward where the breaking waves reach their upper limit. The result is a ridge or berm as in this case at Positano, Italy. The second berm to the left formed earlier by larger waves.

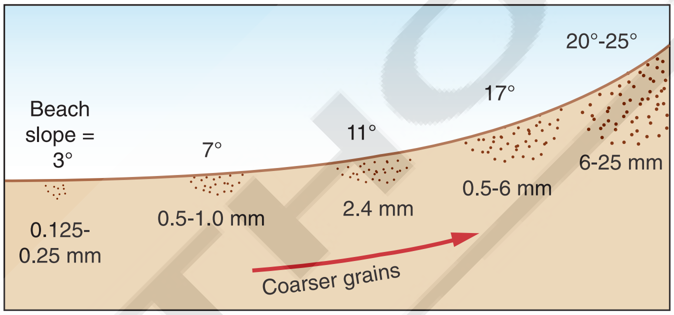


FIGURE 13-13. This graph shows the general relationship between grain size and beach slope.

portion visible in Figure 13-12). This is because the waves use energy stirring sand on the sea bottom so that they slow as they ride up onto the beach. Most of the wave energy is used in waves breaking and moving water and sand upslope. Water flowing back off the beach carries sand with it. The active beach slope is controlled by the grain size being moved and the amount of water carrying the grains. To reiterate, larger grains or less water need a steeper slope to move the grains.

At high tide, the waves reach higher on the beach, so the change in slope continues landward. At low tide, winds pick up the drying sand and blow it landward to form **dunes.** The combination of an upward-curving shoreline, steeper than the average coastal slope, with dunes grown above sea level, builds an offshore barrier island or barrier sandbar. Farther shoreward, the area below sea level is a coastal lagoon (see also Figure 13-3).

Rip Currents

Some high-energy beaches show a prominent scalloped shoreline with cusps 5 to 10 meters apart. These erode as **rip currents** carry streams of water back offshore through the surf after groups of strong incoming waves pile too much water onto the beach. These streams of muddy-looking water can be dangerous to swimmers not familiar with them because the currents are too fast to permit swimming directly back to shore. You can escape a rip current by swimming parallel to shore and then back to the beach. Rip currents are sometimes called undertows, but this is a misnomer because these currents would not drag someone under the surface. The danger comes from a swimmer becoming overtired if they try to swim directly toward shore against the current, possibly ending in drowning.

Loss of Sand from the Beach

Sand in the surf zone moves with the waves; however, where it goes changes with the tides and with wave heights. Larger waves, especially those during a high tide or a major storm, erode sand from the shallow portion of the beach and transport much of it just offshore into less-stirred deeper water. Much of the eroded material comes from the surface of the beach, eroding it to a flatter profile. More comes from the seaward face of dunes at the head of the beach where waves either break directly against the dunes or undercut their face.

Storms bring not only higher waves but also a local rise in sea level—called a **storm surge.** High atmospheric pressure on the sea surface during clear weather holds the surface down, but low atmospheric pressure in the eye of a major storm permits it to rise by as much as a meter or more. The stronger winds of a storm also push the water ahead of the storm into a broad mound several kilometers across. The giant waves of a hurricane and the higher water level of storm surges take these effects to the extreme. They cause massive erosion and decrease the beach slope on barrier islands (see Chapter 14 for further discussion). On gently sloping coasts, they may level the dunes.

As waves break onto a beach, some of the water soaks into the sand and is thus not available to carry sand offshore. This effect is most significant with smaller waves, which have a larger proportion of their water and therefore wave energy soaking into the beach than large storm waves that still have most of their water available to flow offshore


David Hyndman photo.

FIGURE 13-14. These huge interlocking concrete pieces are designed to reduce wave energy and protect the harbor at Nazare, Portugal.

and carry sand with them. Small waves thus tend to leave more of their sand onshore. During low tide, winds pick up drying sand on the beach and blow it landward into dunes. The next strong storm may erode both the beach and the dune face and carry the sand back offshore.

People Move to the Beach

People have always lived along the shores of inlets and bays and fished in nearby streams and lagoons, but their structures along the open coast were temporary shelters that could be moved, or low-value ramshackle summer cabins that could be replaced after storms. Coastal tourism was not important because of the difficulty of access through local brush and the incidence of malaria. By the 1700s, people began building more costly and more permanent structures and even complete towns on the protected landward side of some barrier islands. The old-timers understood beach processes and built homes on stilts on the bay side of the bar with temporary structures at the beach.

By the 1850s, reduction in working hours, formation of an urban middle class with money, and expanded transportation via railroads and steamship service changed the ground rules. Coastal tourism and resorts expanded, especially after the late 1940s. As populations and affluence grew, people installed utilities, paved roads, and built bridges to the islands, along with more expensive permanent homes, hotels, and resorts along the same beaches. More recently, second homes for summer use have become popular, some used for only a few weeks per year. Others have become year-round dwellings for urban retirees.

When hurricanes and other storms damaged these structures, people placed protective **riprap** (▶ Figure 13-14) and seawalls and demanded that local governments protect them from the "ravages of the sea." Instead of living with the sea and its changing beach, they tried to hold back the sea and prevent natural changes to the beach.

For awhile, sediment supply to some beaches increased and erosion decreased. The advent of steam locomotion in the early 1800s, followed by railroads and a large increase in population in the continental interior, also led to deforestation, land cultivation, and overgrazing on a large scale. Invention of the internal combustion engine continued the trend. This removal of protective cover from the land led to heavy surface erosion and large volumes of sediment delivered to the coasts. Along the steep Pacific coast, longshore drift of these sediments caused widespread enlargement of beaches.

Beach Erosion and Hardening

Reduction of Sand Supply

Anything that hinders supply of the sand to the beach from "upstream" on the coast or removes sand from the moving longshore current along the beach results in less sand to an area of coast and erosion of the beach. Dams on rivers trap sand, keeping it from reaching the coast, and mining sand from river channels or from beaches for construction has a similar effect. In many industrial countries, major dam-building periods on rivers began in the 1940s to generate electricity, store water for irrigation, and provide flood control. That and better land use practices caused dramatic reductions in the amount of sediment carried by rivers and supplied to beaches. Beach erosion again accelerated. Shoreline recession of 5 to 10 meters per year was common but was as much as 200 meters per year—for example, at the mouth of the Nile River. The resulting erosion of beaches and coastal cliffs is clear in California.

People with beachfront or cliff-top homes are commonly affected by storms that cause beach erosion or threaten the destruction of their property. Until something bad happens to their beach, beach cliff, or home, however, many do not really think about the constant motion of sand along the beach from waves and offshore movement in storms. Unless tragedy strikes near home, they do not realize that soft sediment beach cliffs gradually retreat landward as they erode at their base and collapse or slide into the ocean.

Artificial Barriers to Wave Action

The distribution of homes and accommodations in North America, where private cars dominate, differs from that in Europe where mass transit is more common. In North America, the main access road leading to the coast feeds a shore road behind beachfront residences and other accommodations. In Europe, the main beach access leads to a road along the beachfront itself. In both cases, a promenade or boardwalk may front the beach near the main access road

Donald Hyndman photo.

▶**FIGURE 13-15.** The massive seawall at Galveston, Texas, was built after the catastrophic hurricane of 1900. Beach sand eroded by waves at the base of the seawall is continually replaced by truckloads of sand brought in from coastal dunes.

Carl Hobbs photo, Virginia Institute of Marine Science.

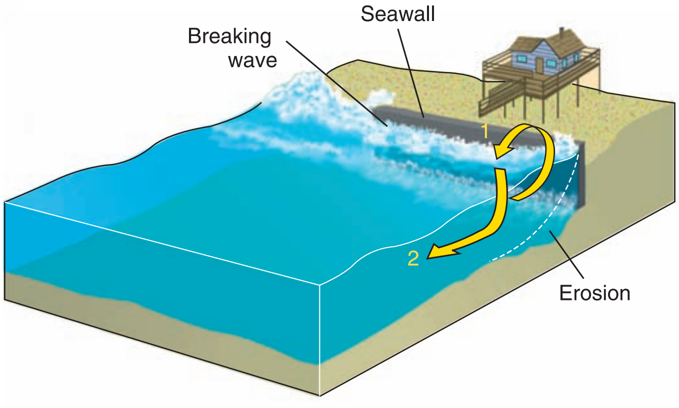
▶**FIGURE 13-16.** The Nor'easter of December 29, 1994, undermined this vertical steel wall at Sandbridge Beach, City of Virginia Beach, Virginia, and toppled into the surf.

and local business district. Seawalls and other supposed beach protection or **hardening** tends to front the boardwalk and spread out along the beach from there.

So what do beachfront dwellers do to protect their property from coastal erosion? Before large-scale tourism, coastal residences and even small communities fell to the waves or moved inland as the beach gradually migrated landward. Shore-protection projects followed the catastrophic Galveston, Texas, hurricane of 1900. These included building the massive **seawalls** (▶Figures 13-15 and 13-16). Individuals during this period reacted to try to stop the erosion threat with boulder piles or walls built of either timber or concrete at the back of the beach and in front of their property. The thought was that the waves will beat against the boulders or walls rather than eroding their property. Construction of seawalls accelerated until the 1960s, when scientists and governments began to recognize that much of these activities have long-term disadvantages.

Waves breaking against coastal cliffs reflect back offshore, carrying smaller particles farther offshore. The same is true when waves break against seawalls or piles of riprap boulders used to protect the area in front of houses. The effect is often just the opposite from what people intended. Although the structure may slow the direct wave erosion of a beach cliff for awhile, the waves reflect back off the barrier, stir sand to deeper levels, and carry the adjacent beach sand farther offshore. On a gently sloping beach, a wave sweeps up onto the beach and the return swash moves back on the same gentle slope. A wave striking a seawall, however, is forced abruptly upward so the swash comes down much more steeply and with greater force, eroding the sand in front of the seawall. The beach narrows and becomes steeper, the water in front of the barrier deepens, and the waves reach closer to shore before they break. Thus, instead of a protected beach, bigger waves approach closer to shore. The result often hastens erosion and removal of the beach. When the water in front of the barrier becomes sufficiently deep, the beach is totally removed, and the waves may undermine the barrier, which then topples into the surf (▶Figures 13-16 and 13-17). If the beach lies at the base of a sea cliff, the supposedly protected cliff succumbs more rapidly as well.

For those who understand that sand grains on a beach tend to migrate along the coast, another approach has been



▶**FIGURE 13-17.** This diagram shows how waves break against a sea wall, causing erosion that may result in the collapse of the seawall as occurred in Virginia Beach.

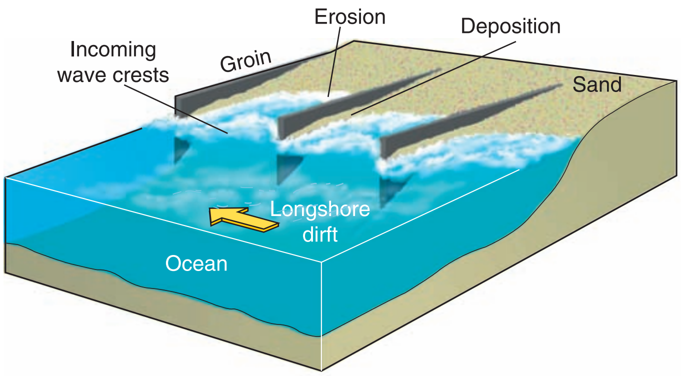


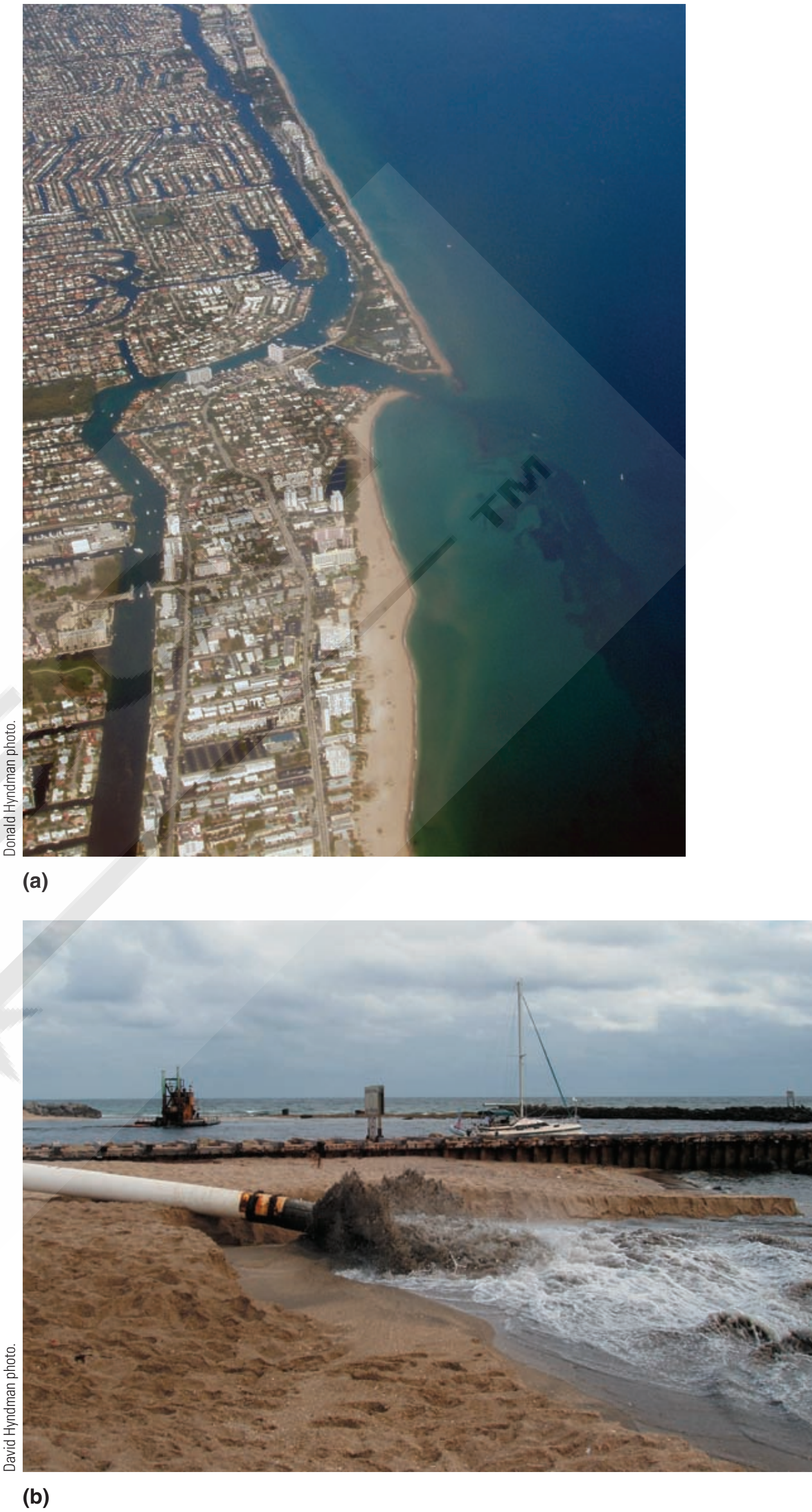
FIGURE 13-18. This diagram shows the effects on beach sand as groins stop longshore drift.


Donald Hyndman photo.

FIGURE 13-19. Groins at Cape May, New Jersey, also trap sand. Longshore drift is from the lower right to left.

to try to keep the sand from migrating. Groins and jetties are built out into the surf or offshore. **Groins,** the barriers built out into the surf to trap sand from migrating down the beach, do a good job of that. They collect sand on their upstream side (Figures 13-18 and 13-19). Unfortunately, that reduces the sand that continues along the beach, which causes beach erosion on the downstream side of the groin. Effectively, they displace the site of erosion to adjacent areas downstream.

Riprap walls or **jetties** are sometimes used to maintain navigation channels for boat access into bays, lagoons, and marinas. Jetties that border such channels extend out through the beach but typically require intermittent dredging to keep the channel open (Figures 13-20 and 13-21). They also block sand migration along the beach. **Break-**


Donald Hyndman photo.

(a)

David Hyndman photo.

(b)

FIGURE 13-20. (a) Jetties bordering an estuary block southward drift of beach sand. That starves the beach to the south, leading to its erosion. Note that the beach south of the estuary is much recessed from the straight coastline. Lighthouse Point, Pompano Beach, Florida. **(b)** Dredging of sand from a river outlet between jetties in Pompano Beach, Florida. The dredge is the yellow boat in the middle left. Sand from this dredging is piped to the downstream side of the jetties to replenish the beach seen in the foreground.

USGS photo.

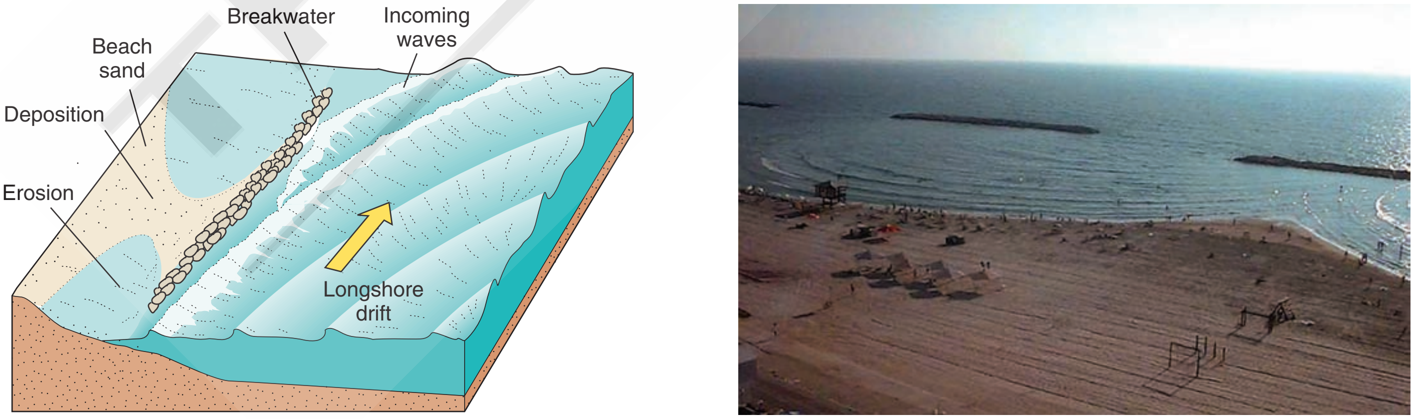
▶**FIGURE 13-21.** Longshore drift is interrupted at jetties just as it is at groins. The beach on the right side of this jetty north of San Diego has been completely eroded by longshore drift of sand from left to right.

waters, built offshore and parallel to the shore, have a similar effect, causing deposition in the protected area behind the barrier and erosion on the downstream or "downdrift" sides (▶Figure 13-22). Both groins and breakwaters trap sand moving along the beach and cause erosion farther down the beach. Without continued supply, those beaches are starved for sand and thus erode away. So, once someone builds a groin or jetty, people downstream see more erosion of their beaches and are inclined to build groins to protect their sections (see Figure 3-18). New Jersey shows these effects to the extreme. Except where replenished, its once sandy beaches are now narrow or nonexistent and lined with groins and seawalls (▶Figure 13-23). The impacts of inlets are dramatic at Ocean City, Maryland, and St. Lucie in Martin County, Florida.

Most knowledgeable people view groins as inherently bad news, and in many cases they are. The state of Florida now requires removal of groins that adversely impact beaches or are simply nonfunctioning. Groins should not stop sand migration permanently—this should only be a remedy until sand is fully deposited on the upstream side. The effects, of course, remain.

However, in some cases groins can work where the drift of sand farther down the coast is undesirable. For example, to keep an inlet open, dredges must remove sand moving down the coast into an inlet. Sand drifting into a submarine valley is generally carried far offshore and lost permanently from the coast (▶Figure 13-24). In such cases, well-engineered groins can provide a useful purpose. They take a wide variety of forms and sizes that depend on the specific purpose. Some even include artificial headlands.

It might seem that continual erosion of sea cliffs and erosion by rivers would add more and more sand to beaches, making them progressively larger. This does hap-



(a)

(b)

Hank Shiffman photo.

▶**FIGURE 13-22.** **(a)** This diagram shows the effects of a breakwater on beach sand. **(b)** Note the deposition of sand behind these breakwaters along the Mediterranean coast of Israel.

S. J. Williams photo, USGS.

▶**FIGURE 13-23.** Houses crowd a narrow barrier bar at Manasquan, New Jersey. A groin in the foreground traps sand moving from left to right. The area downstream to the right, having lost its entire beach, is temporarily protected by a rock seawall.

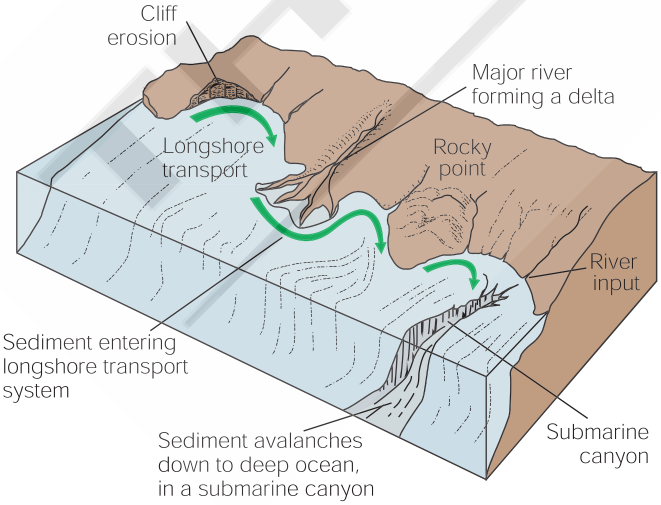
pen in some areas. Beaches are actually gaining sediment near the mouth of the Columbia River between Washington and Oregon, between Los Angeles and San Diego, along much of Georgia and North Carolina, and along scattered patches in Florida and elsewhere on the Gulf of Mexico coast.

However, many coastlines are continuing to erode. What happens to the sand? Nature gets rid of some of it. Some is blown inland to form sand dunes, especially in areas without coastal cliffs. Other processes can permanently remove sand from the system. Some is beaten down to finer grains in the surf and then washed out to deeper water. Rip currents form when waves carry more water onshore than returns in the swash. That current flows back offshore in an intermittent stream that carries some of the beach sand back into deeper water. Huge storms such as hurricanes carry large amounts of sand far offshore.

Some sand drifts into inlets that cross barrier islands, where dredges remove it to keep the inlets open for boat traffic. Some migrates along the coast for a few hundred kilometers until it encounters the deeper water of a **submarine canyon** that extends offshore from an onshore valley. One prominent example of a submarine canyon extends offshore from the Monterey area of central California. These valleys extend across the continental shelf to where the sediment intermittently slides down the continental slope as turbidity flows onto the deep ocean floor. Thus, much of the longshore drifting sand of beaches is permanently lost to the beach environment (▶Figure 13-24).

Areas of Severe Erosion

The main factors in cliff erosion are wave height, sea level, and precipitation. All three factors are heavily influenced by intermittent events such as El Niño and hurricanes. When storms come in from the ocean, their frequency and magnitude strongly affect the rate of erosion. Along the coast of Southern California, erosion is amplified during El Niño events, such as those of 1982–83 and 1997–98 (▶Figure 13-25). Farther north along the coasts of Washington and Oregon, storms are more common during years when El Niño effects are weakest. Much of the West Coast would be eroding back more rapidly except for the presence of beach cliffs almost everywhere. Where these beach cliffs consist of soft Tertiary-age sediments, waves undermine



Modified from Thomas Garrison.

▶**FIGURE 13-24.** The longshore drift of beach sediments often leads to loss of the sediment in a submarine canyon.

U.S. Army Corps of Engineers.

▶**FIGURE 13-25.** Large storm waves pound the shoreline in Eureka, California.

Steven Leatherman photo.

▶FIGURE 13-26. Storm waves undercut this East Coast parking lot, causing it to collapse into the ocean.

them to cause landslides and collapse. Disintegration of the collapsed material supplies sand to beaches down the coast. That part is good for the beach, but if your home is perched at the top of that cliff where there is a magnificent view of the ocean, it may not be so good. As the cliff erodes, your house gets closer to the edge and the view gets better, but your house eventually collapses with the cliff.

Along the Gulf Coast and southeast coast of the United States, storms and heavy erosion are most likely to occur in the hurricane season of late summer to early fall (▶Figure 13-26). The most severe area of coastal erosion in United States, with more than 5 meters of loss per year, is in the area around the Mississippi delta, where dams upstream trap sediment and the compaction of delta sediments lowers their level. One to five meters are lost annually along much of the coasts of Massachusetts to Virginia, South Carolina, and scattered patches elsewhere (▶Figure 13-26). **Nor'easters,** the heavy winter storms that hit the northeastern coast of the United States with similar ferocity, do similar damage.

As mentioned earlier, one of the most extreme cases of **beach hardening** and severe erosion is along the coast of New Jersey (▶Figure 13-27). Early development was promoted by extending a railroad line along more than half of the New Jersey shoreline by the mid-1880s. Buildings first clustered around railroad stations, dunes were flattened for construction, natural dense scrub vegetation was removed, and marsh areas were filled. The arrival of private cars accelerated development. Marsh areas along the back edge of the offshore bars were both filled and dredged in the earliest 1900s to provide boat channels. Inlets across barrier bars were artificially closed, and jetties built after 1911 stabilized others. People did not understand then that barrier bars were part of the constantly evolving beaches, that nature would resist human attempts to control it.

The large population nearby, and the demand for recreation, stimulated the building of high-rise hotels and condominiums in Atlantic City; it is now so packed with large buildings next to the beach that it strongly affects wind flow and the transport of sand. Large-scale replenishment of sand on beaches is widespread in some areas. In other areas, narrow and low artificial dunes are built in front of separate detached houses, as are barriers to provide backup protection from erosion. Groins are numerous. A prominent seawall and continuous groins leave no resemblance either to the original barrier island environment or the beaches that attracted people in the first place.

Beach Replenishment

Are there better ways to protect a beach? Beginning in the 1950s, replacing sand on beaches became popular in the United States. To replace sand on a severely eroded beach, individuals sometimes contract to have sand brought in dump-truck loads (▶Figure 13-28). A simple calculation shows that this is generally a losing proposition.

A large dump truck carries roughly 10 cubic meters

S. J. Williams photo, USGS.

▶FIGURE 13-27. This is the sad ending for a mishandled beach at Cape May, New Jersey. The building of jetties at Cape May Inlet just up the coast trapped the sand that previously replenished the beach. A concrete and rock seawall now lines the "beach."

Donald Hyndman photo.

FIGURE 13-28. A truck dumps rusty, fine-grained sand excavated from the lagoon side of a barrier bar at Holden Beach, North Carolina, following a small storm in March 2001. Such sand is more easily eroded by smaller waves than the natural sand on the beach.

of sand. If a person's lot is 30 meters wide and the beach extends 65 meters from the house to the water's edge at midtide (roughly 2,000 square meters), one dump-truck load would cover that part of the beach to a depth of only half a centimeter or so; it would take 200 loads to add about a meter of sand to the beach in front of one house. Thus, if sand costs $30 per cubic meter, it might take 200 truckloads in front of every home to replace the sand removed in one moderate storm—for a cost of roughly $60,000 for each home. Another problem is that the active beach actually extends well offshore into shallow water. If that part of the beach is not also raised, waves will move much of the onshore sand offshore to even out the overall slope of the beach.

A moderate storm the next month or next year could remove the added sand. How many moderate storms would it take for that type of beach replenishment to reach the value of the house?

And where would the contractor get all that sand? For obvious reasons, mining sand from other beaches is generally not permitted. In some areas, significant sand is obtained from maintenance dredging of sand from navigation channels (▶Figure 13-20b). Mining sand from privately owned sand dunes well back from a beach or dredging sand from a lagoon or other site behind a barrier island is sometimes possible, though expensive. A significant drawback to such sources is that such sand in dunes and lagoons is generally more distinctly fine-grained than that eroded from the beach. Because the storm waves were able to move the coarser-grained sand from the beach, slightly finer-grained sand can be removed by even smaller waves.

Another solution used in many areas, especially along the southeastern coasts, is to dredge sand from well offshore and spread it on the beach. Because much larger equipment is required, regional or federal governments, often under the direction of the U.S. Army Corps of Engineers, normally undertake such projects. If the sand were taken from near shore, that would deepen water near shore and make the beach steeper. Because waves shift sand into an equilibrium slope, that depends especially on the size of the sand grains and the size of the waves. An artificially steeper beach will be eroded down to the equilibrium slope. If the sand is taken from well offshore, below wave base, such so-called **beach replenishment** or **beach nourishment** can work better—at least until the next major storm. The bigger waves of storms erode the beach down to a lower slope farther offshore.

Because many people do not readily understand the processes involved in sand movement in the beach environment, there is no easy solution to where to place the sand during replenishment projects. Most people want to see the sand they pay for placed on the upper dry part of the beach rather than offshore. It is also easier to calculate the volume of sand added to the upper beach and therefore the appropriate cost. Because that location steepens the beach, the next storm will carry much of the new sand offshore, where people view it as lost to the beach and think the replenishment was a waste of money. If half of the sand added is offshore in shallow water where it provides a more natural equilibrium profile, people have a hard time understanding that that sand is not being wasted. Either scenario leads to criticism of beach replenishment as a viable solution to beach erosion. As a result of such problems, some beach experts suggest using the expression "shore nourishment" rather than "beach nourishment" to emphasize that the shallow, underwater part of the beach is equally important. Because subsequent storms remove sand from the beach, part of the cost of a sand renourishment project involves continued small-scale nourishments at intervals of two to six years. Small trucking operations may need to be repeated every year, especially if the added sand is finer-grained than that on the original beach (▶ Figure 13-28).

Nourishment operations generally try to minimize longshore transport and loss of sand from the nourishment site. In some cases, however, a nourishment operation chooses to minimize costs by adding sand up the coast and permitting longshore sand drift to spread sand into the area needing nourishment. Dumping sand at a cape, for example, can lead to sand migration into adjacent bays where it is needed. Similarly, sand drifting into inlets is often lost to the system if inlet dredges dump it far offshore. Some areas such as Florida now require that dredged sand be dumped next to down-drift beaches (▶ Figure 13-20). The operation thus permits the sand to bypass the inlet. Other bypass operations use fixed or movable jet pumps, most commonly along with conventional dredges.

Along cliff-bound coasts, sand, sediment, or easily disintegrated fill material is sometimes merely dumped over an eroding bluff to permit breakup by waves. Instead of rapidly eroding the cliff base, the waves gradually break up the dumped sediment to form new beach material.

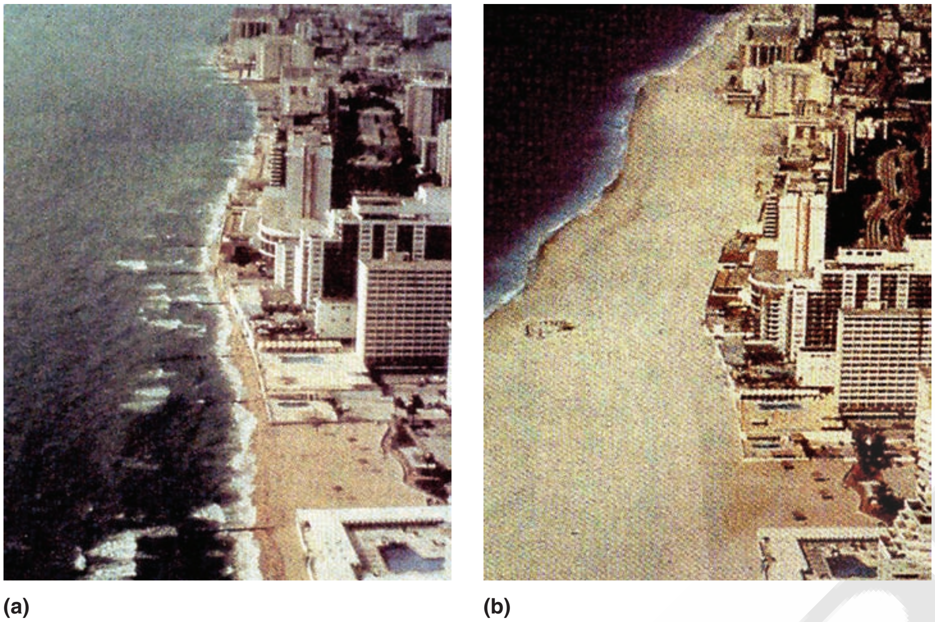
Sometimes, groups of residents, towns, or counties on barrier islands lobby the local, state, and federal governments to replenish the sand on a severely eroded beach. Because large sand-replacement projects typically run into millions of dollars and homeowners do not want their taxes to increase, the local governments lobby their state and federal representatives to have governments foot most or all of the bill. Politicians want to be reelected and to bring as much money back to their communities as possible, so they lobby hard for state and federal funding. What this means, of course, is that the cost of replenishing sand to benefit a few dozen beachfront homeowners is spread statewide or countrywide among all those who derive little to no benefit from the work. For example, the federal government paid approximately 50 percent of the cost of beach replenishment projects in Broward County, Florida, from 1970 to 1991, while local communities paid only 4 percent. To add insult to injury, beachfront communities often try to inhibit beach access by the hoards of mainlanders who flock to the beaches on warm summer days. Although the beach area below high tide is legally public, access routes are often poorly marked or illegally posted for no access. Some communities also make beach access difficult by severely restricting parking along nearby roads.

Where the federal government agrees to foot a large part of the cost of a major beach replenishment project, the U.S. Army Corps of Engineers becomes the responsible agency. Engineers, geologists, and hydrologists with expertise in beach processes design a replenishment project and oversee the private contractors who actually do the work. Common sand sources are shore areas in which sand shows net accumulation or sources well offshore and below wave base. Sometimes sand is dredged off the bottom and transported to the beach area on large barges. Elsewhere sand is suction-pumped from the source and pumped through huge pipes as a sand-and-water slurry. From there, the sand is spread across the beach using heavy earthmoving equipment (▶ Figures 13-29, 13-30, and 13-31).

In fifty-six large federal beach projects in the United States between 1950 and 1993, the Corps of Engineers placed 144 million cubic meters of sand on 364 kilometers of coast. Enormous volumes have been placed in some relatively small areas, such as the 24 million cubic meters on the shoreline of Santa Monica Bay, California. More than 28,000 kilometers of coast continue to erode. Sources of usable sand


Donald Hyndman photo.

▶ FIGURE 13-29. To replenish a beach, the U.S. Army Corps of Engineers pumped a high volume sand-and-water slurry from up the coast in 30-inch pipes. Heavy earthmoving equipment spread more than a meter of sand across the new beach at Ocean Isle Beach, North Carolina, in March 2001.


(a)

(b)

U.S. Army Corps of Engineers photos.

FIGURE 13-30. These views show Miami Beach, Florida, **(a)** before and **(b)** after beach nourishment by the U.S. Army Corps of Engineers.


Peter Shugert photo, U.S. Army Corps of Engineers.

FIGURE 13-31. As part of the massive beach replenishment at East Rockaway, New York, in March 1999, the groin at left minimizes the loss of the replenished sand by longshore drift.

in many areas are being rapidly depleted. Florida's sources of economically recoverable sand, for example, were almost depleted by 1995. They are now looking at tens of billions of tons available from the Great Bahama Banks.

Erosion of Gently Sloping Coasts and Barrier Islands

During the ice ages of the Pleistocene epoch more than 12,000 years ago, sea level dropped as water was tied up in continental ice sheets; the shoreline receded far out onto the continental shelf. In fact, wave-base erosion and deposition to form the continental shelves may be related to thousands of years at which sea levels stood some 100 meters lower than at present. Following the last ice age, as continental ice sheets melted 12,000 to 15,000 years ago and sea level rose, waves gradually moved sands on the continental shelf landward, piling them up ahead of the advancing waves. The Atlantic and Gulf of Mexico coastal plains are gently sloping. The gentle upward-curving **equilibrium profile** of a sandy bottom produced by the waves is steeper than the coastal plain, so it tops off landward in a ridge, the barrier island (Figure 13-32).

Waves sweep sands in from the continental shelf. Offshore **barrier islands** are typically 0.4 to 4 kilometers wide and stand less than 3 meters above sea level. Winds picking up dry beach sands may locally pile dunes as high as 15 meters above sea level. Offshore barrier islands and the lagoons behind them are products of dynamic coastline processes: erosion, deposition, longshore sand drift, and wind transport. Barrier island communities live within this constantly changing environment.

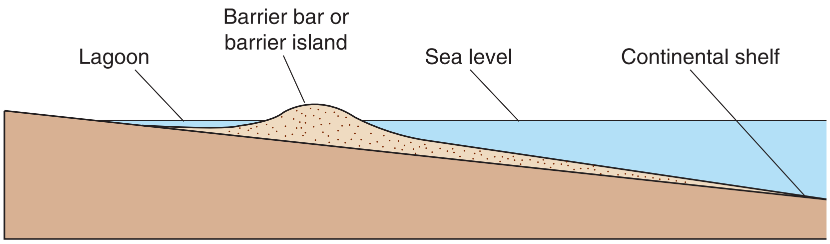


FIGURE 13-32. This cross section shows an offshore barrier bar with a sheltered lagoon behind. The waves create a steeper profile for the sand than the overall slope of the coastline.

Dunes

Sand dunes help maintain the barrier islands. Major storms or hurricanes wash sand both landward into the lagoon and seaward from the barrier bar. Sand moves back up onto the higher beach in milder weather, and wind blows some dry sand into the dunes again. When people modify the dunes, they upset this long-term equilibrium. They level the dunes to build roads, parking areas, and houses, or to improve views of the sea (▶ Figures 13-33). True, they improve the view, but with each storm the beach gets closer until the view gets too good. The house is the next to go. People remove vegetation deliberately to provide views or inadvertently by trampling underfoot to reach the beach or by using off-road vehicles. They move sand onto lagoon-margin marsh areas for housing and marinas. They remove sand from dunes for construction or for reclaiming beaches damaged by erosion elsewhere.

In many places, sand mining is now permitted only offshore at depths greater than 18 to 25 meters. Monitoring of such activities, however, is sometimes lacking. And some communities tacitly condone mining by purchasing beach sand for use on roads. Where dunes are managed at local levels with strong input from landowners, the dunes are often low and narrow to permit easy access to the water and direct views of the ocean. Such low dunes provide, of course, minimal protection from storms.

Wind-blown sand not only builds dunes but also piles against houses and collects as drifts around and downwind of them. In areas of lower sand supply, the wind may funnel between houses to cause areas of local scour. It covers roads, driveways, and sidewalks (see also Figure 13-47, page 347). Where buildings are elevated 4 meters or so on pilings, as is commonly the case across the southeastern or Gulf coasts, the effect on wind-blown sand is much reduced.

After storms, the sand is routinely removed from roads by either individuals or municipal employees. The sand is sometimes placed back on the upper beach, but often it is pushed onto vacant lots where it is lost to the surface of the beach. It may be used to partly rebuild artificial dunes or close gaps opened through the dunes.

Sand can be trapped by placing sand fences across the wind direction to slow the wind and promote deposition of sand on their downwind sides. Fences can help keep sand on the upper beach or in dunes; they can also be used to prevent drifts from forming where they create problems for roads and driveways. Beach nourishment projects also often involve dune nourishment, the sand being scraped from the beach or from overwash sediments.

Coastal vegetation was and in some areas still is burned or physically removed to provide building sites, views, or landscaping. Native vegetation on coastal dunes is effective in reducing sand drift and stabilizing the dunes. Where lost, vegetation can be replanted to help stabilize the sand, though new vegetation may be difficult to establish if the sand is salty or mobile. Straw or branches from local coastal shrubs can be strewn on the sand surface to slow sand movement and help establish the growth of grasses.

Dune vegetation that is diverse and native to the area is best for its likelihood of survival. Natural revegetation of dunes may be accomplished using cuttings taken from nearby mobile dunes, but this can be a slow process. European beach grass introduced to the Pacific coast of the United States has been even more successful in trapping sand than native vegetation, but it creates dunes that are

David Scott photo.

FIGURE 13-33. On this completely built-up barrier island at North Myrtle Beach, South Carolina, the beach in front of the houses has lost its protective dunes. The lagoon behind separates the barrier island from the mainland.


U.S. Fish & Wildlife Service photo.

FIGURE 13-34. Beach sand blown into these dunes along the Oregon coast has been stabilized by European beach grass.

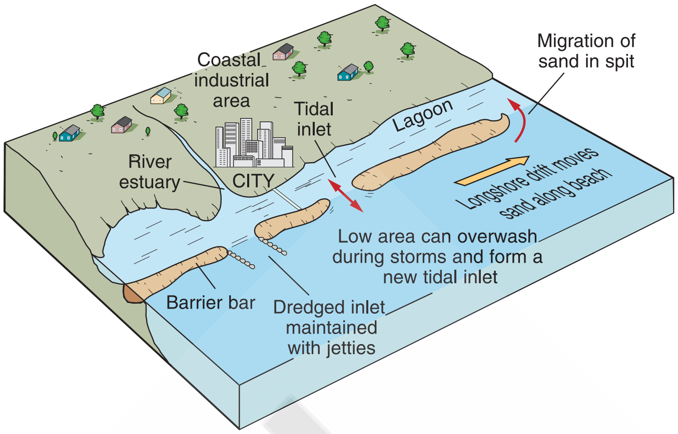


FIGURE 13-35. This diagram shows typical features of barrier bars served by a bridge across the lagoon.

less natural and higher than the originals. It now dominates dunes in coastal Washington state and parts of Oregon (Figure 13-34). Residents, because of appearance, often plant exotic vegetation, but that often requires artificial watering. The resulting rise in the water table can lead to the formation of surface gullies and increase the chance that coastal cliffs will have landslides.

Barrier Bars at Estuaries and Inlets

Offshore barrier bars or barrier islands are a part of the active beach, built up by the waves and constantly shifting by wave and storm action. **Barrier bars** form primarily along gently sloping coastlines such as those of the East and Gulf coasts of the United States, but they also form across the mouths of shallow bays and estuaries along the West Coast. The sea level rise after the last ice age drowned the mouths of these river valleys.

Where high tides or storms carry the sea through low areas in the barrier bars, the water returns from the lagoon to the sea at low tide through the same inlets, eroding them and keeping the channels open (Figure 13-35).

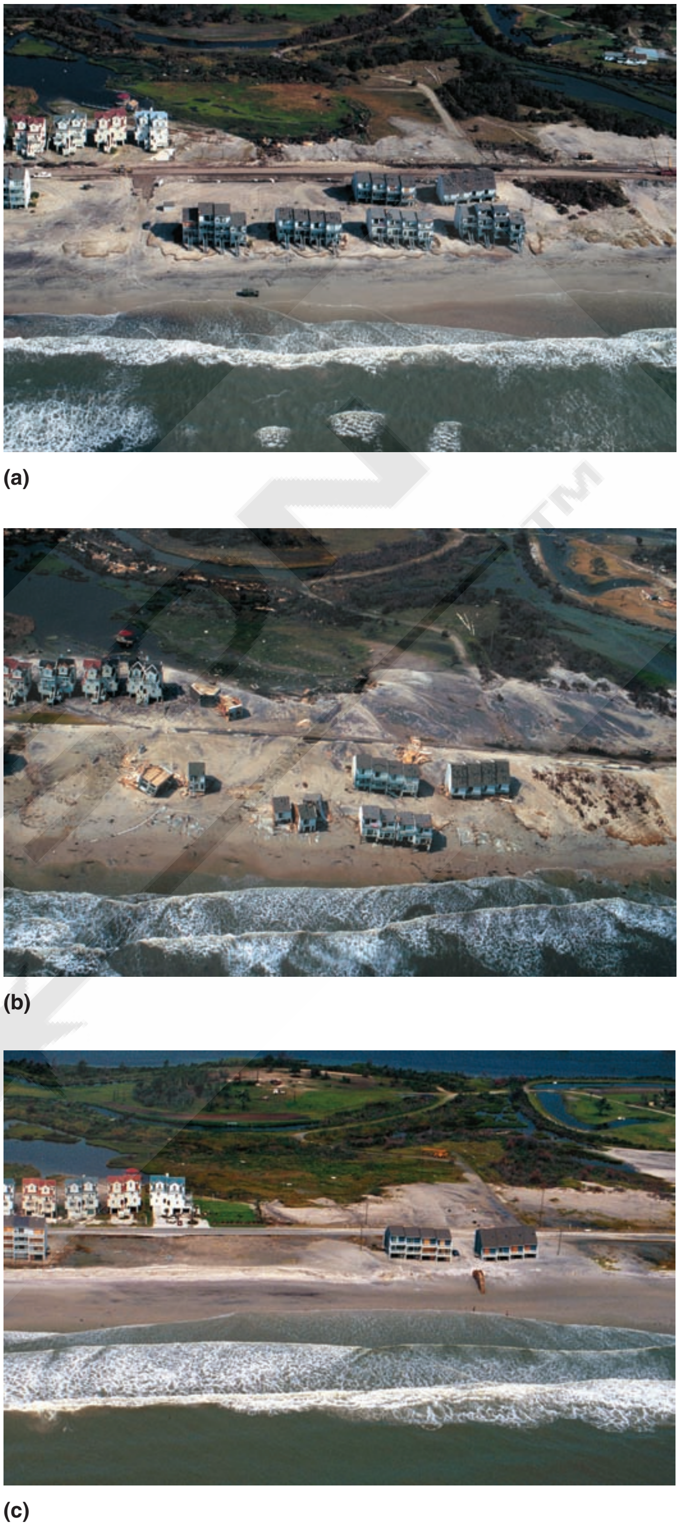
Over time, inlets through barrier bars naturally shift in position; some close and others open. Longshore drift of sand at times closes some gaps and storms open others, so they intermittently change locations. When a storm overwashes and severs a beach-parallel road or a storm cuts a new inlet across a barrier bar, some homes and businesses are isolated on part of the bar (Figure 13-36). Generally, people fill the new inlet and rebuild the road. Unless they do so immediately, the inlet typically widens rapidly over the following weeks or months as tidal currents shift sand into the lagoon and back out. Therefore, the scale of the repair project can quickly get out of hand. A storm at Westhampton, New York, in December 1992, for example, opened a breach inlet 30.5 meters wide. Within eight months, the inlet widened to 1.5 kilometers.

Mark Wolfe photos, FEMA.

FIGURE 13-36. **(a)** This breach of Hatteras Island on the North Carolina outer banks followed the appearance of Hurricane Isabel in September 2003. The ocean is to the right. **(b)** The breach of Hatteras Island following Hurricane Isabel in September 2003 severed the only road along the length of the island and isolated many homes from the mainland. The arrow in **(a)** and the yellow line in **(b)** mark the centerline of the road.

Donald Hyndman photo.

▶**FIGURE 13-37.** This walkway at Sunset Beach, North Carolina, once reached over a protective beachfront dune, which has since been removed by hurricane waves.



(a)

(b)

(c)

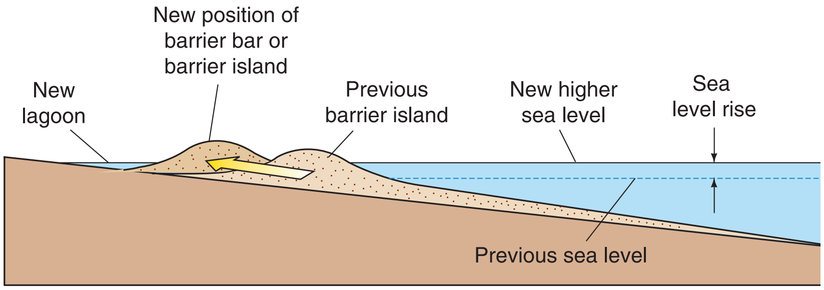
USGS photos.

▶**FIGURE 13-38.** Shoreward migration of beach at North Topsail Beach, North Carolina, is well shown by a series of three views of the same area. **(a)** Use the colorful condominiums in the upper left here as a reference and note those in the center of the photo taken after Hurricane Bertha on July 16, 1996. **(b)** This is the same location following Hurricane Fran on September 7, 1996. Finally, **(c)** shows the same location after Hurricane Bonnie on August 28, 1998. Note that the series of photos spans only about two years.

Shifting sand closing an existing inlet commonly hinders access to marinas and boating in the protected lagoon behind the bar. It also hampers sea access to any coastal industrial sites on the mainland (▶Figure 13-35). Thus, existing inlets are often kept open by dredging and by building jetties along the edges of the inlet. Where significant populations or large industrial sites are affected, the U.S. Army Corps of Engineers can be involved in constructing or maintaining an inlet. Where significant settlement has occurred on or behind a barrier bar, the maintenance of inlets severely hinders natural evolution of the barrier bar and beach (▶Figures 13-19 and 3-37).

Many barrier islands are now so crowded with buildings that they bear little resemblance to their natural state. Most distinctively, the former broad beaches erode in front of the buildings (▶Figures 13-27 to 13-31 and 13-33). Although the barrier islands help protect low-lying coastal areas from damage from storm waves and floods, the islands themselves are hazardous places to live. Through past experience with hurricanes and other big storms, people living on barrier bars learn to build homes on posts, raising them above the higher water levels and bigger waves of some storms. In many areas, building codes require such construction. Codes also require preservation of beachfront dunes to help protect buildings from wave attack. Unfortunately, most dunes along much of the coasts of the southeastern and Gulf Coast states have disappeared in spite of such efforts. Beach erosion is severe (▶Figures 13-37 to 13-43).

Barrier islands migrate with the gradual rise of sea level. Because the equilibrium slope of the beach and the position of the barrier island are linked to the size of the waves and the depth of water, the beach and barrier island must shift landward as the water level rises. Current rates of sea-level rise are approximately 30 centimeters per century. On



▶FIGURE 13-39. The barrier island migrates landward as the sea level rises.

especially gentle-sloping coasts like those of the southeastern United States, that 30-centimeter rise can move sand of the beach and barrier island inland by 100 to 150 meters or more (▶Figures 13-39, 13-40, and 13-41). **Barrier island migration** happens over decades, but all of the significant movement is in stages during hurricanes and other major storms (▶Figure 13-41).


Orrin Pilkey photo.

▶FIGURE 13-40. The Morris Island Lighthouse, near Charleston, South Carolina, was on the beach in the 1940s. It is now 400 meters offshore because the sand of the barrier island on which it once stood gradually migrated landward.

Oysters grow in the quiet waters of lagoons on the coastal side of barrier islands. If you find oyster shells in sand of the front beach, one possibility is that the barrier bar gradually migrated landward, over the mud of the lagoon. Beach waves winnow out the fine mud of the lagoon, leaving the heavier oyster shells embedded in the beach sand (▶Figure 13-42). Migrating barrier bars also overwhelm trees growing along lagoons; their stumps reappear later along the upper edge of the beach as the bar gradually moves landward after a storm (▶Figure 13-43).

A coastal construction control line (CCCL), established in the 1980s by the Department of Protection of Florida, imposed higher standards for land use and construction in high hazard coastal zones. It restricts the purchase of flood insurance to those communities that adopt and enforce National Flood Insurance Program construction requirements governed by the standard building code. On the coastal side of the CCCL, requirements are more stringent for foundations, building elevations, and resistance to wind loads (FEMA, 1998).

There are a few barrier bars at the mouths of drowned river estuaries along the West Coast; people build on those just as they do on barrier islands on the East Coast (▶Figure 13-44). On gently sloping areas of some Western beaches,


Ruth Flanagan photo, courtesy of Pipkin & Trent.

▶FIGURE 13-41. Storm waves reduced the level of sand by almost 4 meters during one storm at Westhampton, New York. The barrier island migrated landward, leaving these houses stranded offshore.


Donald Hyndman photo.

▶FIGURE 13-42. These oyster shells embedded in beach sand at Myrtle Beach, South Carolina, probably originated in a back bay or lagoon behind the barrier bar.

Carl Hobbs photo, Virginia Institute of Marine Science.

▶**FIGURE 13-43.** Peat blocks and stumps in the surf at Sandbridge Beach, City of Virginia Beach, originally formed in the lagoon behind the barrier island decades ago. The island has since migrated landward over the lagoon. Note the imposing wall supposedly protecting buildings from the waves.

as in parts of Southern California, people build right on the beach (▶Figures 13-45 and 13-46). Perhaps they purchase homes or build them in good weather, not realizing that big winter waves come right up to the house. Some pile heavy riprap on the beach in front of their homes, hoping to protect them (▶Figure 13-45). The protection is temporary because big waves reflect off the boulders, washing away the beach sand in front and steepening the remaining beach. Eventually, the boulders will slide into the wave-eroded trough, leaving the homes even more vulnerable. But then the beach is gone.

Some houses are built on pilings to let waves pass underneath. Bigger storm waves will impact such structures because any protective dunes have long since disappeared. Sand still blows off the beach, but it drifts around the houses instead of forming dunes in the back beach. It piles against the houses and covers sidewalks and streets. Shoveling snow in some northern areas can be hard work but imagine

Donald Hyndman photo.

▶**FIGURE 13-44.** As viewed across a lagoon, homes cover a bay mouth bar south of Lincoln City, Oregon.

Donald Hyndman photo.

▶**FIGURE 13-45.** These beachfront homes are protected, albeit temporarily, by heavy riprap, northwest of Oxnard, California.

California Coastal Records photo.

▶**FIGURE 13-46.** These huge houses are right on the beach at Oxnard Shores in Southern California.

Donald Hyndman photo.

▶**FIGURE 13-47.** Sand blown off a beach (out of sight on the right) piled as drifts around houses and covered roads, sidewalks, and driveways in Oxnard in Southern California. Shoveling snow in northern climates is heavy work, but this is ridiculous. "For Sale" signs are often numerous along this beach-parallel street.

having to shovel sand, which weighs many times as much and will not melt (▶Figure 13-47).

Erosion Along Cliff-Bound Coasts

Hard, erosionally resistant rocks, granites, basalts, hard metamorphic rocks, and well-cemented sedimentary rocks mark some steep coastlines. Such coastlines often consist of rocky headlands separated by small pocket coves or beaches. Much of the coast of New England, parts of northern California, Oregon, Washington, and western Canada are of this type. The rocky headlands are subjected to intense battering by waves and drop into deep water. Sands or gravels pounded from the headlands are swept into the adjacent coves, where they form small beaches (see Figures 13-10b and 13-11).

Raised marine terraces held up by soft muddy or sandy sediments less than 15 million to 20 million years old mark other coastlines, including much of the coasts of Oregon and central California. These terraces, standing a few meters or tens of meters above the surf are soft and easily eroded. They were themselves beach and near-shore sediments not long ago. Some terraces rose during earthquakes as ocean floor was stuffed into the oceanic trench at an offshore subduction zone. Elsewhere they may rise by movements associated with California's San Andreas Fault.

Along these coasts, cliffs line the head of the beach, except in low areas at the mouths of coastal valleys. The beaches consist of sand, partly derived from erosion of the soft cliff materials and partly brought in by longshore drift. Waves strike a balance between erosion and deposition of beach sands. Larger waves flatten the beach by taking sand farther offshore, and smaller waves steepen it. Where streams bring in little sand or the cliffs are especially resistant, the beach may be narrow. Where rivers supply much sand or where the coastal cliffs are easily eroded, the beach may be wide. A broad, sandy beach hinders cliff erosion because most of the waves' energy is expended in stirring up sand and moving it around.

With European settlement of North America over the past 200 years and our attempts to control nature, we have upset that balance. We have severely reduced the supply of river sediment to the coasts by building dams that trap the sediment and by mining sand and gravel from streams. We have even mined sand and gravel from beaches themselves. With less sand and gravel, beaches shrink and the waves break closer to, and more frequently against, coastal cliffs. Waves undercut the cliffs, which collapse into the surf (▶Figures 13-48 to 13-52).

Unfortunately, people also choose to build houses on

Donald Hyndman photo.

(a)

David Hyndman photo.

(b)

▶**FIGURE 13-48.** **(a)** Beach erosion and cliff collapse endangered homes in Pacifica (south of San Francisco) in March 1998. Collapsed parts of houses litter the base of the cliff. **(b)** Taken from the same viewpoint as **(a)** in December 2003, this photo shows that the seven homes nearest the camera are gone. Only two of the original ten houses remain, and one of these sold in 2004 for $450,000! (See Figure 18-2, page 446.)

USGS photo.

FIGURE 13-49. Heavy equipment tried desperately to pile heavy riprap boulders at the base of the same rapidly eroding cliff shown in Figure 13-48 before the next high tide in January 1998. Note the house debris at the base of the cliff.

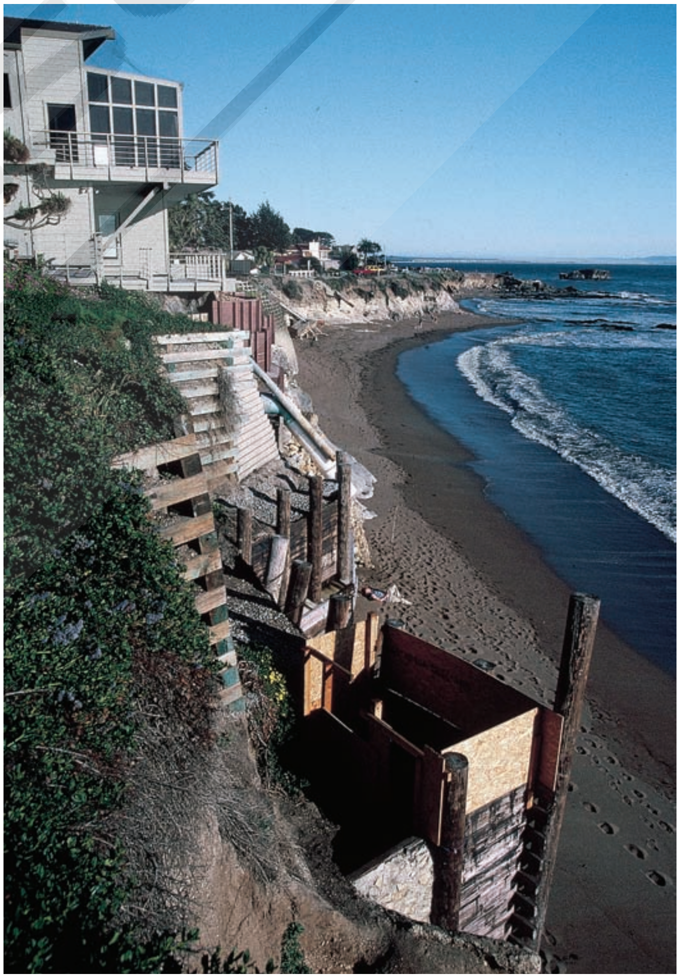
Donald Hyndman photo.

FIGURE 13-50. Collapsing sea cliffs at Ocean Beach near San Diego destroyed some homes and severely threatened those remaining in March 1998. Huge boulders were placed at the base in an attempt to arrest the erosion.

those same cliff-tops so they have a view of the sea, typically not realizing how hazardous the sites are. Developers promote building in such locations as prime view lots, charging a premium for land that may be gone in a few years or decades. Vertical cliffs made of soft, porous sediments are a recipe for landsliding and cliff collapse (Figures 13-48 to 13-52). Homeowners themselves exacerbate the problem by clearing the beach of driftwood that would help to break the force of the waves. They unwittingly become agents of erosion by making paths down steep slopes, cutting steps, and excavating for foundations next to the cliffs. They irrigate vegetation and drain water into the ground from rooftops, driveways, household drains, and sewage drain

California Coastal Records photo.

FIGURE 13-51. These large homes sit atop a sea cliff without a beach in Pismo Beach in Southern California. Note that a new house is being built on the right, even though established houses have lost most of their yards and have spray cemented their cliffs to slow cliff loss.



Donald Hyndman photo.

FIGURE 13-52. Timbers were installed in an attempt to protect an eroding beach cliff below houses in Pismo Beach, California.

▶**FIGURE 13-53.** These homes were built on pilings on the beach west of Malibu, California.

Donald Hyndman photo.

fields. Adding water to the ground further weakens it and promotes landslides.

When such cliff-top dwellers see their property disappearing and recognize that part of the problem is waves undercutting the cliff, the typical response is to dump coarse rocks—riprap—at the base of the cliff (▶Figures 13-48b, 13-49, and 13-50) or to build a wood, steel, or concrete wall there (▶Figures 13-51 and 13-52). Waves reaching such a resistant barrier tend to break against it, churn up the adjacent sand and sweep it offshore. The new deeper water next to the barrier undercuts the barrier, which then collapses into the deep water. The barrier has provided short-term protection to the cliff but after a few years that "cure" is worse than if they had done nothing. A bigger slab of the cliff collapses into the deeper water in the next big storm. Some people spray **shotcrete,** a cement coating, on the surface of the cliff to minimize the loss of the cliff surface (▶Figure 13-51).

In a few places, people even build at the base of cliffs, on the beach itself (▶Figure 13-53). They must know something that we do not! CalTrans, the California highway department, had enough sense to build the coastal highway 6 or so meters above high tide; these houses, on the beach side of the highway, are on pilings sunk into the beach but have their lower floors more than 3 meters below the highway.

Letting Nature Take Its Course

A less expensive, more permanent, alternative to beach hardening or beach replenishment is advocated by many coastal experts. They suggest moving buildings and roads on gently sloping coasts back landward to safer locations after major damaging storms. Sand dunes behind the beach can be stabilized with vegetation in order to provide further protection for areas behind them. The cost of moving buildings may be high, but it is less than the continuing long-term cost of maintaining beach-hardening structures that tend to destroy the beach or continually bringing in thousands of tons of beach sand that is removed by the next storm. And it does provide a way of living with the active beach environment rather than forever trying to fight it.

On cliff-bound coasts, buildings should not be placed close to cliffs. Those that are too close should be moved well back from them, and foot traffic and other activities should be restricted to areas away from the cliff tops and faces. Beaches should not be cleared of natural debris such as driftwood. Mining sand and gravel from beaches and streams should be prohibited. Additional dams should not be built on rivers that discharge in coastal regions with erosion problems; removal of old dams would eventually bring more sediment back to the beaches and help to protect the cliffs.

KEY POINTS

✓ Most waves are caused by wind blowing across water. The height of the waves is dictated by the strength, time, and distance of the wind blowing over the water. **Review p. 327.**

✓ Water in a wave moves in a circular motion rather than in the direction the wave travels. That circular motion decreases downward to disappear at an approximate depth of half the wavelength. Waves begin to feel bottom near shore in water less than that depth. **Review p. 327; Figures 13-2 and 13-3.**

- ✓ Wave energy is proportional to the wavelength times wave height squared, so doubling the wave height quadruples the wave energy. **Review p. 328; Sidebar 13-3.**
- ✓ The grain size and amount of sand on a beach depends on wave energy, erodibility of sea cliffs and the size of particles they produce, and the size and amount of material brought in by rivers. Larger winter waves commonly leave a coarser-grained, steeper beach. **Review p. 329.**
- ✓ Waves approaching the beach at an angle push sand parallel to shore as longshore drift. **Review pp. 329–330; Figures 13-9 and 13-10.**
- ✓ A beach at its equilibrium profile steepens toward shore. Larger waves erode the beach and spread sand on a gentler slope. **Review pp. 331–332; Figures 13-12 and 13-13.**
- ✓ Beach hardening to prevent erosion or stop the longshore drift of sand includes seawalls, groins, and breakwaters. All have negative consequences either after a period of time or elsewhere along the coast. In some cases, they result in the complete loss of a beach. **Review pp. 333–336; Figures 13-14, 13-15, 13-16, 13-21, and 13-23.**
- ✓ Beach replenishment or nourishment involves replacing sand on a beach, an expensive proposition that needs to be repeated at intervals. **Review pp. 338–341; Figures 13-20, 13-28 to 13-31.**
- ✓ Offshore barrier bars or barrier islands develop where the landward-steepening beach profile is steeper than the general slope of the coast. Wind blows sand shoreward into dunes. Dune sand spreads over the beach, helping to protect it from erosion during storms, but most dunes have disappeared by excavation, trampling underfoot, or wave action. **Review pp. 341–343; Figures 13-28 to 13-30, 13-37 and 13-38.**
- ✓ Estuaries and inlets through barrier bars are kept open by tidal currents into the lagoon behind the bar. Storm surges and waves open, close, and shift the locations of such inlets. **Review pp. 343–344; Figures 13-35 and 13-36.**
- ✓ Barrier islands maintain their equilibrium profile by migrating shoreward with rising sea level. Because many barrier islands are now covered with buildings, the island cannot migrate but is progressively eroded. **Review pp. 344–345; Figures 13-39 to 13-43.**
- ✓ Along cliff-bound coasts, sand is eroded from headlands and deposited in bays. Where the cliffs are made of soft materials, decreasing amounts of sand fed by rivers results in more rapid cliff erosion with disastrous consequences for buildings atop the cliffs. **Review pp. 345–347.**

IMPORTANT WORDS AND CONCEPTS

Terms

barrier bar, p. 343
barrier island, p. 341
barrier island migration, p. 344
beach hardening, p. 333
beach nourishment, p. 339
beach replenishment, p. 339
breakwater, p. 335
dune, p. 331
equilibrium profile, p. 341
fetch, p. 327
groin, p. 334
hardening, p. 333
headland, p. 331
jetty, p. 334
longshore drift, p. 328
Nor'easter, p. 328
rip current, p. 332
riprap, p. 333
sand dune, p. 341
seawall, p. 333
shore profile, p. 331
shotcrete, p. 349
storm surge, p. 332
submarine canyon, p. 337
wave energy, p. 328
wavelength, p. 327
wave refraction, p. 329

QUESTIONS FOR REVIEW

1. Sketch the motion of a stick (or a water molecule) in a deep-water wave.
2. What force creates most waves?
3. How can there be big waves at the coast when there is little or no wind?
4. Why are ocean waves generally larger than those on lakes?
5. Which side of a beach groin collects sand?
6. How do sand dunes affect stability of a beach?
7. Where does the sand go that is eroded from a beach during a storm?
8. What factors cause growth of wind waves?
9. Where would a sand spit form on a barrier bar island relative to the direction of longshore drift?
10. What happens to wave energy and erosion when riprap or seawalls are installed?
11. Draw the shape of a barrier bar island before and after a significant rise in sea level.

FURTHER READING

Assess your understanding of this chapter's topics with additional quizzing and conceptual-based problems at:

http://earthscience.brookscole.com/hyndman.